Search for Anomalous Production of Diphoton Events with Missing Transverse Energy at CDF and Limits on Gauge–Mediated Supersymmetry–Breaking Models

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Abstract

We present the results of a search for anomalous production of diphoton events with large missing transverse energy using the Collider Detector at Fermilab. In 202 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV we observe no candidate events, with an expected standard model background of $0.27 \pm 0.07(\mathrm{stat}) \pm 0.10(\mathrm{syst})$ events. The results exclude a lightest chargino of mass less than 167 GeV/c^2, and lightest neutralino of mass less than 93 GeV/c^2 at 95% C.L. in a gauge–mediated supersymmetry–breaking model with a light gravitino.

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The standard model (SM) [1] of elementary particles has been enormously successful, but it is incomplete. For theoretical reasons [2,3], and because of the '$ee\gamma\gamma$+missing transverse energy ($\not\!\!E_T$)' [4] candidate event recorded by the CDF detector in Run I [5], there is a compelling rationale to search in high–energy collisions for the production of heavy new particles that decay producing the signature of $\gamma\gamma + \not\!\!E_T$. Of particular theoretical interest are supersymmetric (SUSY) models with gauge–mediated SUSY–breaking (GMSB). Characteristically, the effective SUSY–breaking scale (Λ) can be as low as 100 TeV, the lightest SUSY particle is a light gravitino ($\widetilde{G}$) that is assumed to be stable, and the SUSY particles have masses that may make them accessible at Tevatron energies [2]. In these models the visible signatures are determined by the properties of the next–to–lightest SUSY particle (NLSP) that may be, for example, a slepton or the lightest neutralino ($\widetilde{\chi}_1^0$). In the GMSB model investigated here, the NLSP is a $\widetilde{\chi}_1^0$ decaying almost exclusively to a photon and a $\widetilde{G}$ that penetrates the detector without interacting, producing $\not\!\!E_T$. SUSY particle production at the Tevatron is predicted to be dominated by pairs of the lightest chargino ($\widetilde{\chi}_1^{\pm}$) and by associated production of a $\widetilde{\chi}_1^{\pm}$ and the next–to–lightest neutralino ($\widetilde{\chi}_2^0$). Each gaugino pair cascades down to two $\widetilde{\chi}_1^0$'s, leading to a final state of $\gamma\gamma + \not\!\!E_T + X$, where X represents any other final state particles.

In this paper we summarize [6] a search for anomalous production of inclusive $\gamma\gamma+\not\!\!E_T+X$ events in data corresponding to an integrated luminosity of 202 ± 12 pb^{-1} [7] of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the CDF II detector [8]. We examine events with two isolated photons with $|\eta| \lesssim 1.0$ and $E_T^\gamma > 13$ GeV for the presence of large $\not\!\!E_T$. This work extends a previous CDF search [5] for SUSY in this channel by using an upgraded detector, a higher $p\bar{p}$ center-of-mass energy, and a larger data sample. The analysis selection criteria have been re-optimized to maximize, *a priori*, the expected sensitivity to GMSB SUSY based only on the background expectations and the predictions of the model. Similar searches for diphoton + $\not\!\!E_T$ events have been performed elsewhere [9].

We briefly describe the aspects of the CDF II detector relevant to this analysis. The magnetic spectrometer consists of tracking devices inside the 3-m diameter, 5-m long superconducting solenoid magnet operating at 1.4 T. A 90-cm long silicon micro-strip vertex detector, consisting of one single–sided layer and six double–sided layers, with an additional

double–sided layer at large η, surrounds the beam pipe. Outside the silicon detector, a 3.1-m long drift chamber with 96 layers of sense wires is used with the silicon detector to determine the momenta of charged particles and the z position of the $p\bar{p}$ interaction (z_{vertex}). The calorimeter, constructed of projective towers, each with an electromagnetic and hadronic compartment, is divided into a central barrel that surrounds the solenoid coil ($|\eta| < 1.1$) and a pair of 'end-plugs' that cover the region $1.1 < |\eta| < 3.6$. The hadronic compartments of the calorimeter are also used to provide a measurement of the arrival time of the particles depositing energy in each tower. Wire chambers with cathode–strip readout (the CES system), located at shower maximum in the central electromagnetic calorimeter, give 2-dimensional profiles of showers. A system of proportional wire chambers in front of the central electromagnetic calorimeters (the CPR system) uses the one-radiation-length-thick magnet coil as a 'preradiator' to determine whether showers start before the calorimeter [10]. Muons are identified with a system of planar drift chambers situated outside the calorimeters in the region $|\eta| < 1.0$.

We select candidate events using both online (during data taking) and offline selection requirements. Online, events are selected for the presence of two photon candidates, identified by the three-level trigger as two isolated electromagnetic clusters [10] with $E_T^\gamma > 12$ GeV, or two electromagnetic clusters with $E_T^\gamma > 18$ GeV and no isolation requirement. The offline event selection requirements for the diphoton candidate sample are designed to reduce electron and jet/π^0 backgrounds while accepting well-measured diphoton candidates. We require two central (approximately $0.05 < |\eta| < 1.0$) electromagnetic clusters that: a) have $E_T^\gamma > 13$ GeV; b) are not near the boundary in ϕ of a calorimeter tower [11]; c) have the ratio of hadronic to electromagnetic energy, Had/EM, $< 0.055 + 0.00045 \cdot E^\gamma(\mathrm{GeV}^{-1})$; d) have no tracks, or only one track with $p_T < 1$ GeV/c, extrapolating to the towers of the cluster; e) are isolated in the calorimeter and tracking chamber [12]; f) have a shower shape in the CES consistent with a single photon; g) have no other significant energy deposited nearby in the CES.

To minimize the number of events with large $\not\!\!E_T$ due to calorimeter energy mismeasurement, we correct for jet (j) energy loss in cracks between detector components and for nonlinear calorimeter response [13]. To avoid any remaining cases where a jet is not

fully measured by the calorimeter, we remove events based on the azimuthal opening angle between the $\not\!\!E_T$ direction and the ϕ of any jet with uncorrected $E_T > 10$ GeV, $\Delta\phi(\not\!\!E_T, j)$. We require all events to have $10^\circ < \Delta\phi(\not\!\!E_T, j) < 170^\circ$. To reduce beam–related and cosmic–ray backgrounds we require a good vertex with $|z_{\text{vertex}}| < 60$ cm and reject events with significant energy out-of-time with the collision [14]. These backgrounds can also produce $\not\!\!E_T$ equal in magnitude and opposite in direction to a photon, or to the vector sum of the momenta of two photons if they are nearby in ϕ. In this case an event is rejected if there are potential cosmic–ray hits in the muon chamber, within 30 degrees of the photon, that are not matched to any track. Events are also rejected if there is a pattern of energy in the calorimeter indicative of beam–related backgrounds [15]. A sample of 3,306 diphoton events pass all candidate selection requirements. The $\not\!\!E_T$ requirement, $\not\!\!E_T > 45$ GeV, is determined by the final optimization procedure that is discussed below, after a more complete description of the backgrounds.

Before the $\not\!\!E_T$ requirement, the diphoton candidate sample is dominated by QCD interactions producing combinations of photons and jets faking photons. In each case only small measured $\not\!\!E_T$ is expected, due mostly to energy measurement resolution effects. Standard CDF techniques [10] are used to estimate the individual contributions for the sample to be $47 \pm 6\%$ γj, $29 \pm 4\%$ $\gamma\gamma$, and $24 \pm 4\%$ jj production. To estimate the shape of the $\not\!\!E_T$ distribution of this background we use a control sample of similarly-produced events that have the same calorimetric response and resolution. We select 7,806 events that pass the same photon E_T, z_{vertex}, fiducial, $\Delta\phi(\not\!\!E_T,j)$, beam–related and cosmic–ray background selection requirements, but are allowed to satisfy looser photon identification and isolation requirements [16]. If an event is in the diphoton candidate sample it is rejected from the control sample. The contribution from $e\gamma$ events, discussed below, is also subtracted from the control sample. Since the $\not\!\!E_T$ resolution for a given event is a function of the sum of all the transverse energy in the event (ΣE_T), and we observe a small difference between the ΣE_T distributions of the diphoton candidate and control samples, we correct the $\not\!\!E_T$ in the control sample for this difference [17]. To predict the number of events with large $\not\!\!E_T$, we normalize the corrected control sample distribution to the number of diphoton candidate events in the region $\not\!\!E_T < 20$ GeV, and fit the spectrum above 10 GeV to a double

exponential. We predict $0.01 \pm 0.01(\text{stat}) \pm 0.01(\text{syst})$ events with $\not\!\!E_T > 45$ GeV, where the uncertainty is dominated by differences in the predictions using various control sample selection requirements, the choice of fit function, and the statistical uncertainties of the sample.

Events with an electron and a photon candidate ($W\gamma \rightarrow e\nu\gamma$, $Wj \rightarrow e\nu\gamma_{fake}$, $Z\gamma \rightarrow ee\gamma$, etc.) can contribute to the diphoton candidate sample when the electron track is lost (by tracking inefficiency or bremsstrahlung) to create a fake photon. For W decays large $\not\!\!E_T$ can come from the neutrinos. This background is estimated using $e\gamma$ events from the data. The diphoton triggers accept electromagnetic clusters with tracks so they provide an efficient and unbiased sample of these events. We find 462 $e\gamma$ events before the $\not\!\!E_T$ requirement. Examining a $Z \rightarrow ee$ sample, we estimate $1.0 \pm 0.4\%$ of electrons will pass the diphoton candidate sample requirements, including charged track rejection. By multiplying the number of observed $e\gamma\not\!\!E_T$ events by the probability that an electron fakes a photon, we estimate $0.14 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$ background events in the sample with $\not\!\!E_T > 45$ GeV. The uncertainty is dominated by the statistical uncertainty in the fake rate and the uncertainty in the purity of the $e\gamma$ sample.

Beam–related sources and cosmic rays overlapped with a SM event can contribute to the background by producing spurious energy deposits that in turn affects the measured $\not\!\!E_T$. While the rate at which these events contribute to the diphoton candidate sample is low, most contain large $\not\!\!E_T$. The spurious clusters can pass photon cuts. The dominant contribution actually comes from sources that produce two photon candidates at once, such as a cosmic muon undergoing bremsstrahlung twice. This background is estimated from the data using a sample of events with no primary collision and two electromagnetic clusters, multiplied by the rate that clusters from cosmic rays pass the diphoton candidate sample requirements. Backgrounds where only one of the photons, or only the $\not\!\!E_T$, is from a non-collision source, are estimated to be negligible. The total number of events expected from non–collision sources in the $\not\!\!E_T > 45$ GeV sample is $0.12 \pm 0.03(\text{stat}) \pm 0.09(\text{syst})$. The uncertainty includes the uncertainty in the rate that spurious clusters pass the diphoton selection requirements and takes into account the statistics and purity of the sample of events with no primary collision.

The $\not\!\!E_T$ distribution of the diphoton candidate sample, see Figure 1, shows good agreement with that from the expected backgrounds. Table I summarizes the number of observed events and predicted backgrounds with four different $\not\!\!E_T$ requirements. There are no events with $\not\!\!E_T > 45$ GeV.

Since there is no evidence for events with anomalous $\not\!\!E_T$ in the diphoton candidate sample, we set limits on new particle production from GMSB using the parameters suggested in Ref. [18]. To estimate the acceptance for this scenario we generate GMSB events using ISAJET [19] with CTEQ5L parton distribution functions [20]. The production cross sections from ISAJET are corrected by a K-factor of approximately 1.2 to match the next-to-leading order (NLO) prediction [21]. We process the events through the GEANT-based [22] detector simulation, and correct the resulting efficiency with information from data measurements.

Since electrons and photons interact similarly in the calorimeter we investigate the efficiency of the photon identification and isolation selection criteria by using a control sample of electrons from $Z \rightarrow ee$ events. Separate efficiency estimates comparing data and detector simulation agree to within 3%. Using the simulation we estimate that if a photon within the fiducial portion of the detector is isolated, it has an 80% probability of passing the identification and isolation criteria. However, the isolation energy of the photons is predicted from the Monte Carlo to be a strong function of the SUSY scale due to the number and energy of the extra jets produced. We find, for example, the single–photon efficiency to be reduced to 62% at $M_{\tilde{\chi}_1^{\pm}}$=170 GeV/c^2. This has a significant impact on the sensitivity. We find that the fraction of generated signal events passing all the selection requirements, including $\not\!\!E_T > 45$ GeV, rises linearly from 3.5% at $M_{\tilde{\chi}_1^{\pm}}$=100 GeV/c^2 to approximately 8% at 180 GeV/c^2. It remains roughly flat for larger masses due to the increasing inefficiency of the $\Delta\phi(\not\!\!E_T, j)$ selection requirement. The relative systematic uncertainty in the efficiency of the photon identification and isolation requirements is approximately 6.5% per photon. Other significant uncertainties in the Monte Carlo model predictions are from initial/final state radiation (10%), Q^2 of the interaction (3%) and uncertainty in parton distribution functions (5%). Combining these numbers with the 6% luminosity uncertainty gives a total relative systematic uncertainty of 18%.

The kinematic selection requirements defining the final data sample are determined by

a study to optimize the expected limit, *i.e.*, without looking at the signal region data. To compute the expected 95% confidence level (C.L.) cross section upper limit we combine the predicted signal and background estimates with the systematic uncertainties using a Bayesian method [23] and follow the prescription described in Ref. [24]. The expected limits are computed as a function of $\not\!\!E_T$, photon E_T, and $\Delta\phi(\not\!\!E_T,j)$ selection requirements. We find that the best limit is predicted with the selection described above for the diphoton candidate sample, and $\not\!\!E_T >$ 45 GeV. The statistical analysis indicates that the most probable expected result, in the absence of a signal, would be an exclusion of $M_{\widetilde{\chi}_1^\pm}$ less than 161 GeV/c^2 and $M_{\widetilde{\chi}_1^0}$ less than 86 GeV/c^2.

In the data signal region, with $\not\!\!E_T >$ 45 GeV, we observe zero events. Taking into account the 18% systematic uncertainty we set a 95% C.L. upper limit of 3.3 signal events. Figure 2 shows the observed cross section limits as a function of $M_{\widetilde{\chi}_1^\pm}$ and $M_{\widetilde{\chi}_1^0}$ along with the theoretical LO and NLO production cross sections. Using the NLO predictions we set a limit of $M_{\widetilde{\chi}_1^\pm} > 167$ GeV/c^2 at 95% C.L. From mass relations in the model, we equivalently exclude $M_{\widetilde{\chi}_1^0} < 93$ GeV/c^2 and $\Lambda < 69$ TeV.

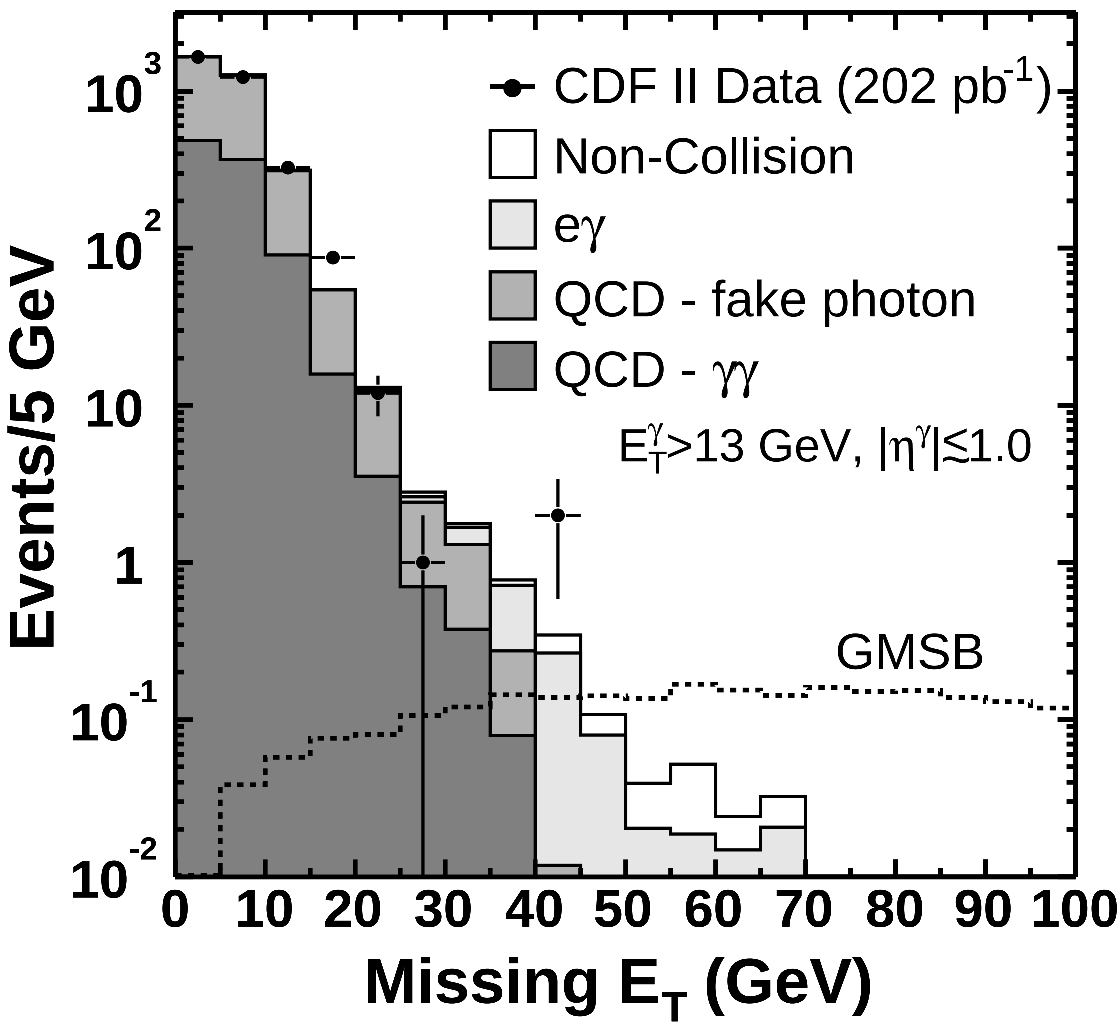

FIG. 1. The $\not\!\!E_T$ spectrum for events with two isolated central photons with $E_T^\gamma > 13$ GeV and $|\eta| \lesssim 1.0$ along with the predictions from the GMSB model with a $\widetilde{\chi}_1^\pm$ mass of 175 GeV/c^2, normalized to 202 pb^{-1}. The diphoton candidate sample data are in good agreement with the background predictions. There are no events above the $\not\!\!E_T > 45$ GeV threshold. The properties of the two candidates above 40 GeV appear consistent with the expected backgrounds.

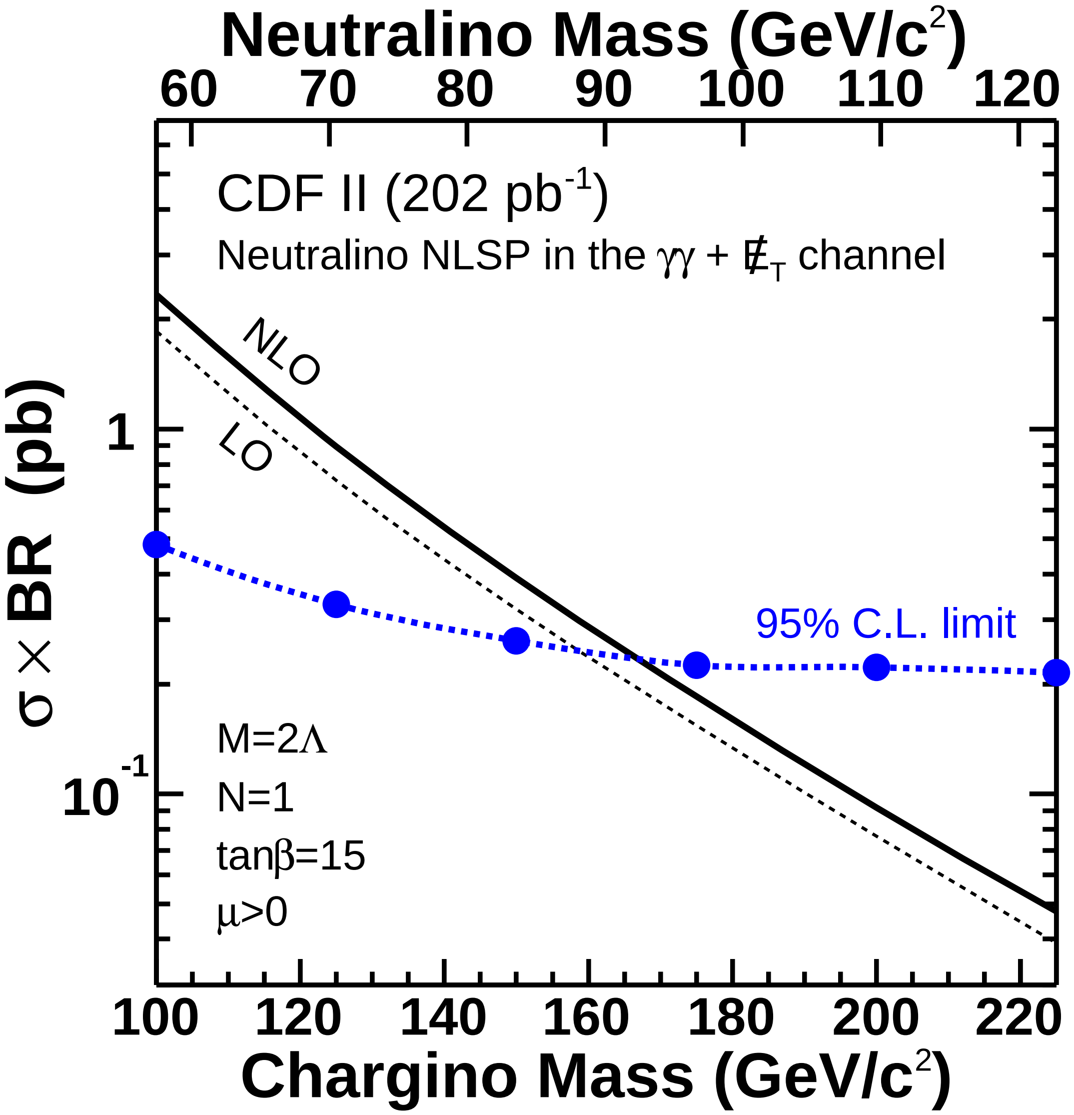

FIG. 2. The 95% C.L. upper limits on the total production cross section times branching ratio versus $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ for the light gravitino scenario using the parameters proposed in [18]. The lines show the experimental limit and the LO and NLO theoretically predicted cross sections. We set limits of $M_{\tilde{\chi}_1^\pm} > 167$ GeV/c^2 and $M_{\tilde{\chi}_1^0} > 93$ GeV/c^2 at 95% C.L.

In conclusion, we have searched 202 pb^{-1} of inclusive diphoton events at CDF run II for anomalous production of missing transverse energy as evidence of new physics. We find good agreement with standard model expectations. We find no events above the *a priori* $\not\!\!E_T$ threshold, and thus observe no new $ee\gamma\gamma\not\!\!E_T$ candidates. Using these results, we have set limits on the lightest chargino $M_{\tilde{\chi}_1^\pm} > 167$ GeV/c^2 and $M_{\tilde{\chi}_1^0} > 93$ GeV/c^2 at 95% C.L. in a GMSB model. This limit is an improvement over previous CDF and DØ limits and is

comparable to LEP II for similar models [9].

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TABLES

$\not\!\!E_T$ Requirement	Expected				Observed
	QCD	$e\gamma$	Non-Collision	Total	
25 GeV	$4.01 \pm 3.21 \pm 3.76$	$1.40 \pm 0.52 \pm 0.45$	$0.54 \pm 0.06 \pm 0.42$	$5.95 \pm 3.25 \pm 3.81$	3
35 GeV	$0.30 \pm 0.24 \pm 0.22$	$0.84 \pm 0.32 \pm 0.27$	$0.25 \pm 0.04 \pm 0.19$	$1.39 \pm 0.40 \pm 0.40$	2
45 GeV	$0.01 \pm 0.01 \pm 0.01$	$0.14 \pm 0.06 \pm 0.05$	$0.12 \pm 0.03 \pm 0.09$	$0.27 \pm 0.07 \pm 0.10$	0
55 GeV	(negligible)	$0.05 \pm 0.03 \pm 0.02$	$0.07 \pm 0.02 \pm 0.05$	$0.12 \pm 0.04 \pm 0.05$	0

TABLE I. Numbers of events observed and events expected from background sources as a function of the $\not\!\!E_T$ requirement. Here "QCD" includes the $\gamma\gamma$, γj and jj processes. The first uncertainty is statistical, the second is systematic.

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